June 11, 2008

Fabrication of Six 1.3 GHz Single-Cell SRF Niobium Cavities for FNAL

Final Report

Niowave, Inc.
&
Roark Welding and Engineering Co., Inc.

Summary

Niowave and Roark have fabricated six 1.3 GHz single-cell SRF niobium cavities for FNAL, in order to quality both vendors for ILC nine-cell SRF cavity work. Duration of project was eight months, from late September 2007 to early June 2008. Completed intermediate steps include CAD modeling, eddy current scanning, tooling and die design and fabrication, half cell and end tube fabrication, CMM analysis, electron beam welding, and frequency measuring. Six fully welded cavities have been frequency and QA tested to ensure all specifications were met. Two additional cavities were completed and may be purchased by FNAL for additional testing. Once the cavities undergo final cleaning and chemical processing, they will be tested for high field RF performance at FNAL.

Cavity Design and Material Properties

The 1.3 GHz single cell cavity was drawn using SolidWorks software, modeling DESY's design provided by Fermi. An assembly drawing can be seen in the Appendix. The 3D SolidWorks model of the fabricated cavity is shown in Figure 1.1 below. Prints are included in the project package.

Figure 1.1 3D model of 1.3 GHz single cell, including Nb attachment rings and NbTi flanges

Table 1.1 lists key properties of the niobium used for fabrication. More extensive material specifications, including chemical composition and mechanical properties, are included in the quality assurance (QA) report.

Table 1.1 Properties of niobium

RRR	Grain Size	Nb Wall Thickness
>300	ASTM #6 (> 50 μm)	2.8 mm

Dies and Fixtures

Dies necessary for stamping and forming the cavity tubes and cells were fabricated and are shown in Figure 1.2(a). Weld fixtures, Figure 1.2(b,c), necessary for electron beam welding were also fabricated. All forming dies and fixtures were made of 7075 or 6061 aluminum. Welding fixtures were made of stainless steel and shimmed with high RRR niobium.

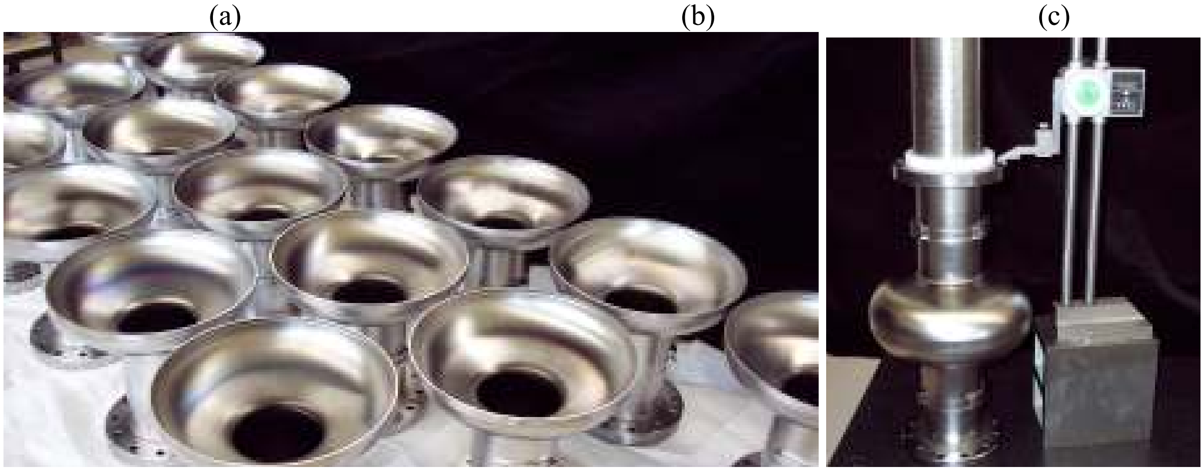
(a) (b) (c)

Figure 1.2 (a) stamping dies and machining fixtures; (b) attachment ring weld fixture; (c) iris weld fixture

Fabrication and RF Check

Eight sets of cells, tubes, attachment rings, and niobium-titanium flanges have been stamped and machined for assembly of eight single cell 1.3 GHz cavities; two extra sets were made for engineering analysis by Niowave/Roark. Figure 1.3 shows photographs of cavity components at different stages of fabrication. Quality assurance has been implemented between each stage of fabrication and will be presented in the QA report.

(a) (b) (c)

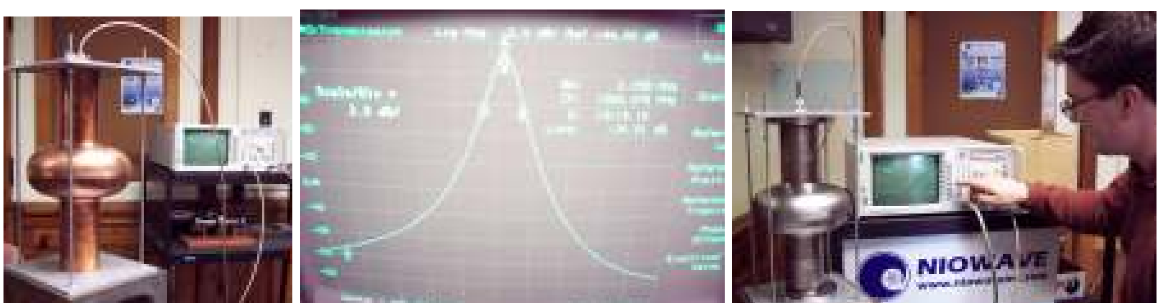


(d) (e)

Figure 1.3 (a) trimming a half cell; (b) quality assurance of trimmed half cell; (c) beam tubes after EB welding; (d) half cell assemblies after iris welds; (e) cavity length check after iris welds (weight on top)

A copper cavity was first fabricated to confirm a frequency of 1.3 GHz, shown in Figure 1.4(a). Two niobium half cells were stamped for coordinate measuring machine (CMM) analysis. The results showed that the half cells had sprung back out of tolerance, a common reaction of niobium. The half cells were then coined within tolerance and verified with CMM/AutoCAD analysis by both Roark/Niowave and FNAL.

The half cells were machined leaving extra material on the iris and equator. The iris was trimmed 0.35 mm beyond the ellipse, leaving material for weld shrinkage, while the equator was left long for both weld shrinkage and frequency tuning (0.35 mm + 2 mm, respectively). Under the experimental setup shown in Figure 1.4, the frequency of the niobium cavity was measured. Frequency was checked after trimming 0.5 mm from one half cell equator, then measured again after trimming 0.5 mm off the mating half cell equator. The data was analyzed by Niowave's tuning program to predict the frequency before and after weld shrinkage. The results are shown in Figure 1.5.



(a) (b) (c)

Figure 1.4 (a) copper cavity frequency test; (b) RF parameters displayed by network analyzer; (c) niobium cavity frequency test after iris welds

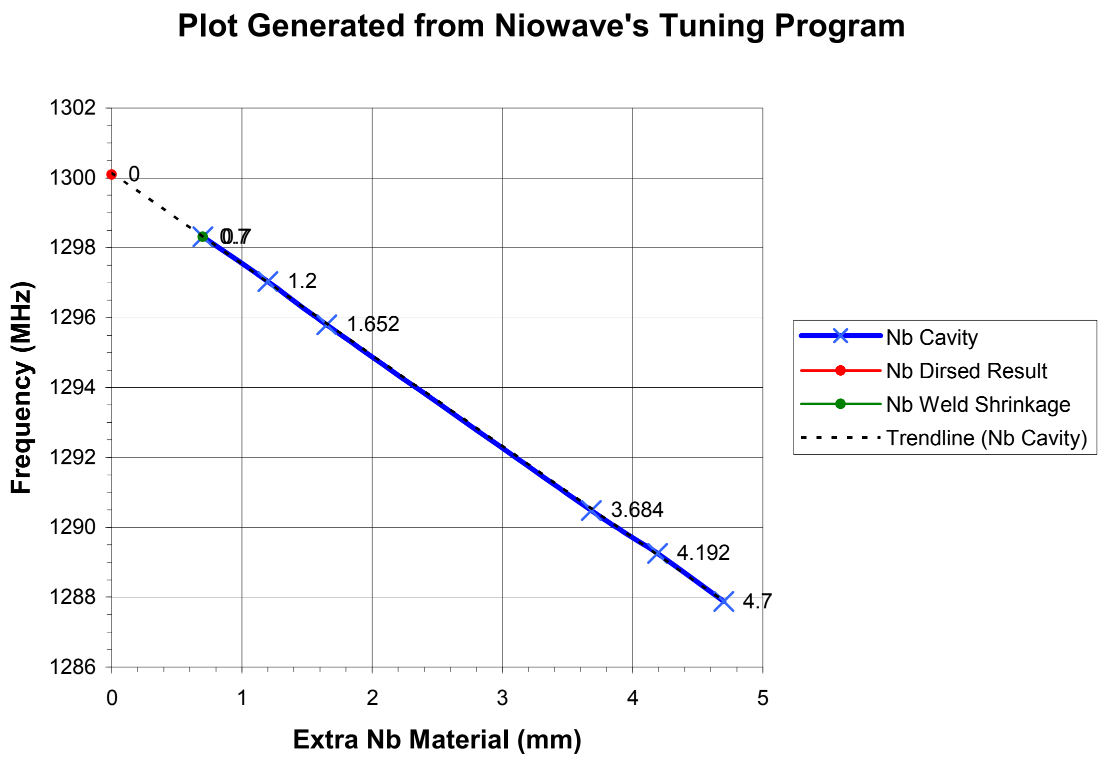


Figure 1.5 Niobium frequency measurements and predicted final frequencies using Niowave's tuning program

Results of the tuning program concluded that the cavities will measure within one MHz of the desired 1300 MHz, leaving just enough material for weld shrinkage. Welding, etching, and cool-down all shift frequency. Any minor differences after these steps will be tunable at this level. A second set of half cells was machined in the same manner to check repeatability. The results mirrored the first two half cells. As a result, the remaining half cells were all machined to weld shrinkage dimensions; to ensure consistency they were spot checked.

The tube assemblies and half cells were then prepared for iris welds. Four iris welds were performed at Roark in the presence of FNAL employees, Scott Reeves and Paul Olderr.

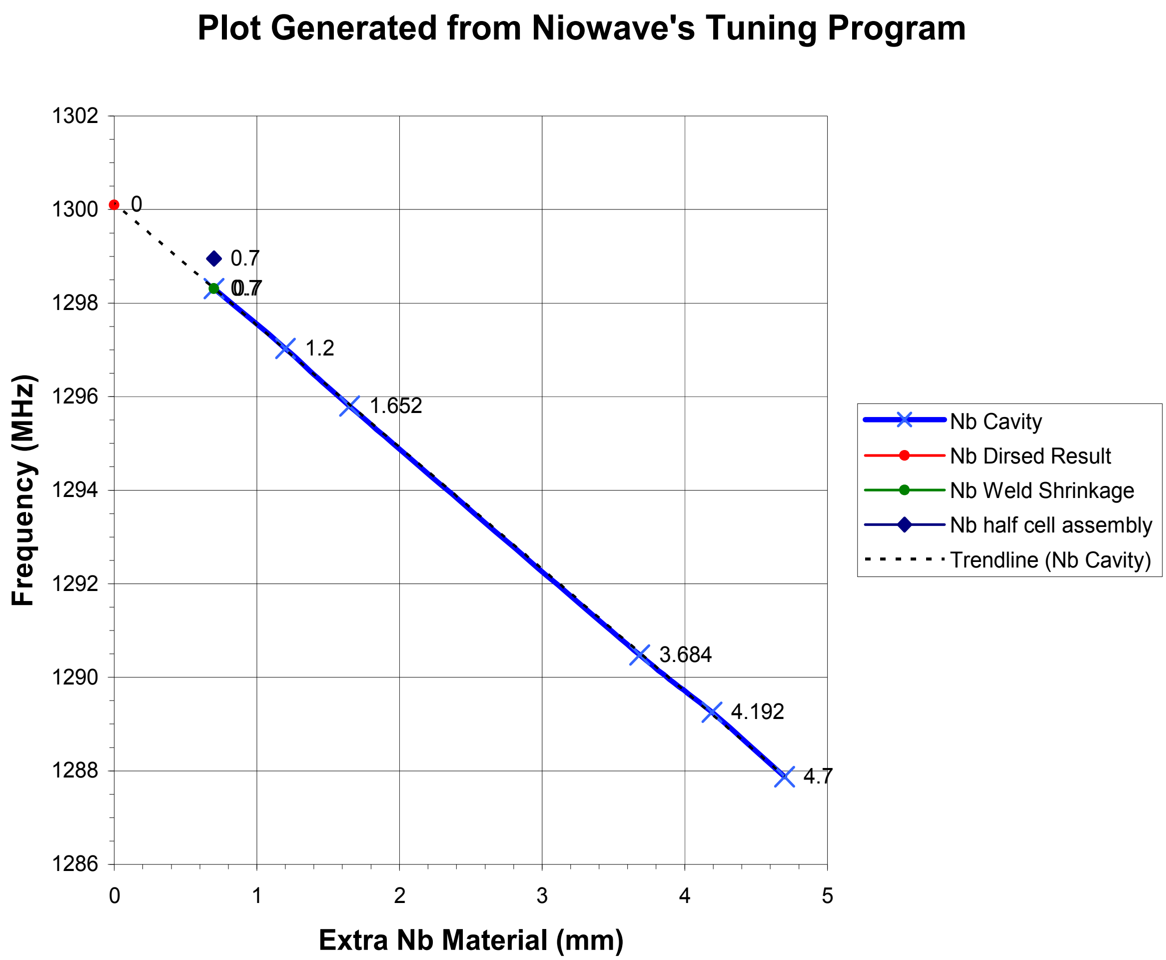


Figure 1.6 Niobium half-cell assembly frequency measurements (after iris welds) compared with previous measurements

Frequency results yielded a 1298.92 MHz average after iris welds and before equator welds (Figure 1.6 above). Overall length measured 393.4 mm on average. Cavity design accounted for 0.7 mm equator weld shrinkage. Frequency, Q, and cavity lengths after equator welds are tabulated in the *Post Weld Results* section of this report.

Cleaning and Acid Etching

Each cavity component was cleaned in a class 100 certified cleanroom at Niowave, and the Nb cells and tubes were "buffered chemical polishing" (BCP) etched prior to electron beam welding (Figure 1.7). Components were cleaned following standard cleanroom procedures and BCP etched for 10 minutes at a rate of 2 μm/min.

Parts were shipped to/from Roark and Niowave in cleanroom bags filled with dry nitrogen to minimize surface oxidization and contamination before EBW. Certification of all component processing has been documented in the QA report.

(a) (b)

Figure 1.7 (a) niobium half-cell assemblies being processed in class 100 cleanroom; (b) BCP chemical etching preparing for equator welds

Electron Beam Welding (EBW)

The cavities were electron beam welded at Roark. The order of weld operation follows:

1) Full penetration seams welds to seal tubes
2) NbTi flange to tube weld (inner and outer)
3) Attachment ring to tube seal welds
4) Iris welds (outer, then inner)
   - Fermi present for first round
5) Full penetration equator welds
   - Fermi and Niowave present

All welds were performed in a vacuum held below DESY's specification of 5×10^{-5} mbar (3.75×10^{-5} torr) (Figure 1.8). Weld coupons were studied prior to cavity welds. After each equator weld was performed, the inside bead was inspected to ensure a smooth, full penetration weld, seen in Figure 1.8(b,c). Weld parameters are included in the QA report. RRR samples will be tested at Niowave in the weeks to come and results will be reported to FNAL.

(a) (b) (c)

Figure 1.8 (a) full penetration equator weld; (b) inside equator weld inspection; (c) inside equator weld bead

Post Weld Results

Table 1.2 lists the frequency, quality factor (Q), overall cavity length and attachment ring span for all eight fabricated cavities after equator welds. Table 1.3 lists frequencies and Q values of four cavities to further verify the cavity shape. Measurements were taken at room temperature, atmospheric pressure, and before the final chemical etch of ~150 µm. Average weld shrinkage at the iris was 0.30 mm and 0.58 mm at the equator. Iris shrinkage was significantly less because the welds were not full penetration. Therefore, the lengths of the cavities measure at the high end of the tolerance. Overall length specification is 392 mm +/- 1 mm.

Table 1.2 Room temperature frequency and Q measurements after equator welds

Cavity	Frequency (MHz)	Q	Overall Cavity Length (mm)	Ring-to-Ring Length (mm)
NR-1	1300.873	9800	393.0	225.4
NR-2	1300.381	9700	393.0	225.1
NR-3	1300.473	9800	392.9	225.2
NR-4	1300.676	9800	392.8	224.9
NR-5	1300.420	9800	392.8	225.1
NR-6	1300.107	9700	392.6	224.8
NR-7	1299.332	9500	392.4	225.1
NR-8	1299.892	9700	393.0	224.8

Table 1.3 HOM frequency and Q measurements after equator welds

	HOM 1		HOM 2	
Cavity	Frequency (MHz)	Q	Frequency (MHz)	Q
NR-1	1656.96	5000*	1835.67	9000
NR-2	1657.55	9400	1835.11	9200
NR-4	1657.61	9000	1835.41	8500
NR-5	1658.62	9500	1835.18	8800

*Degenerate modes overlapped

Deliverables

- Six single-cell cavities (two additional cavities available)
- Final written report
  - Project overview
- Quality assurance report
  - Material data sheets: Nb & NbTi
  - CAD drawings
  - Operation and inspection reports
- Oral power point presentation at FNAL

Future/Follow-on Work

1) Chemically etch single-cells
2) Etch other cavities (spoke, 9-cell)
3) Frequency tuning
4) Test cavities
5) Fabricate 9-cell 1.3 and 3.9 GHz cavities

APPENDIX

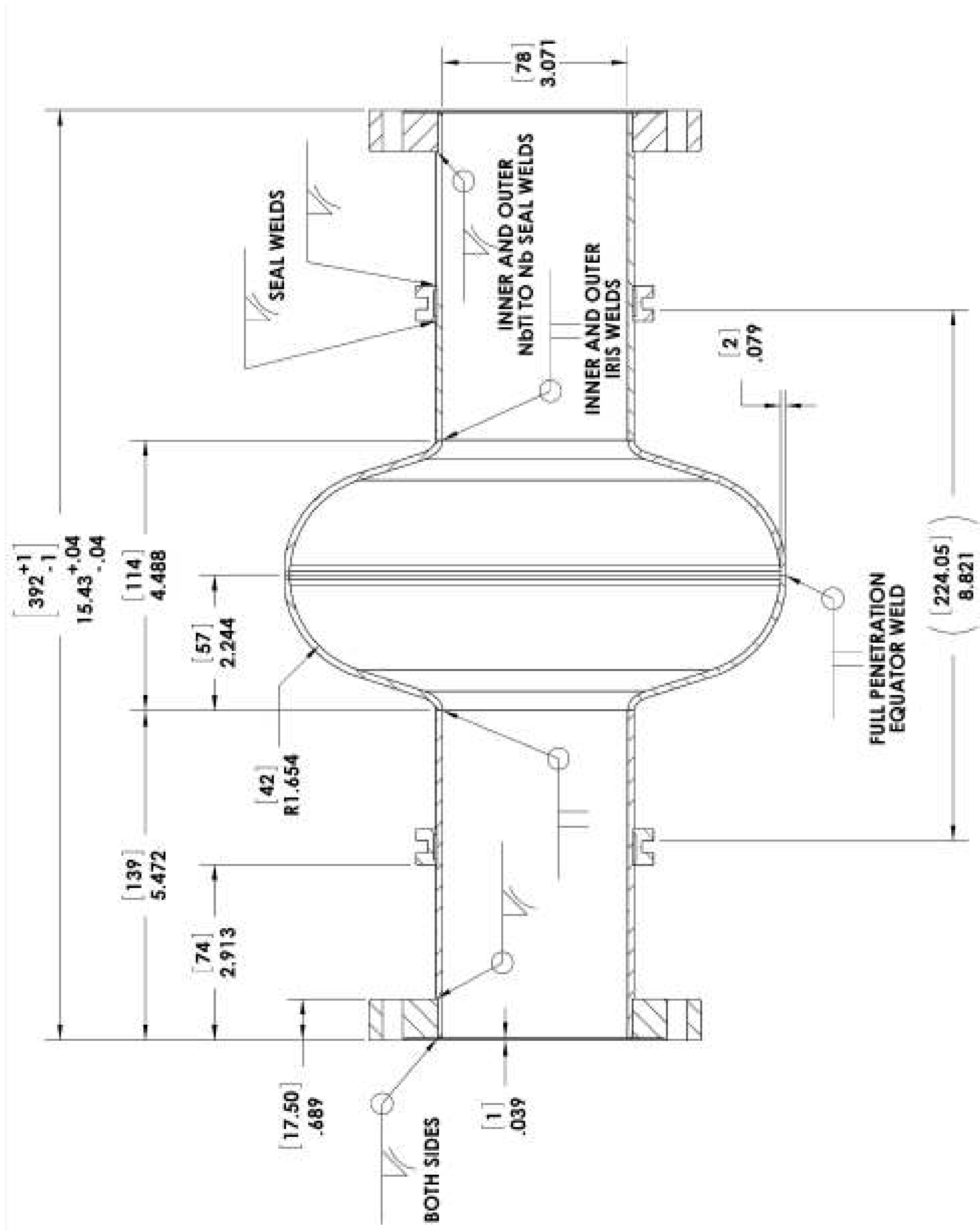


Figure 1.4 Assembly drawing of 1.3 GHz single cell including dimensions and weld joints